Thermodynamic Assessment of Air-Cycles for Ultra-Low-Temperature Refrigerated Container Applications

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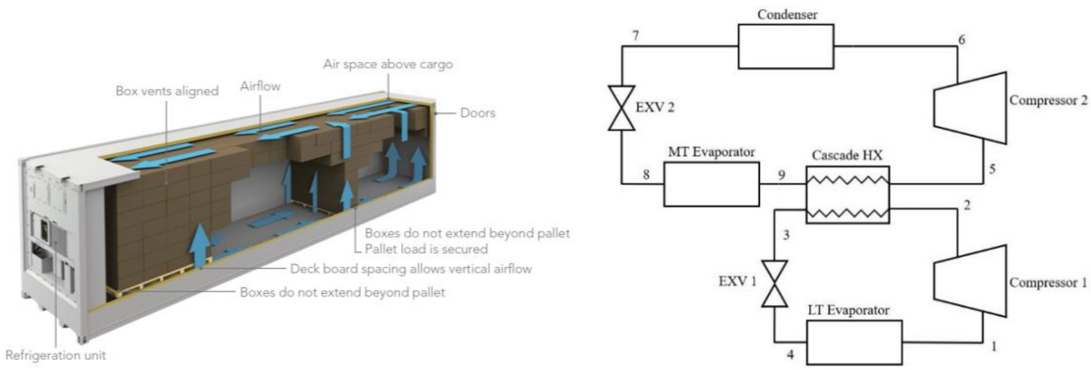
ABSTRACT

The demand for low-temperature refrigeration systems increased due to the ongoing COVID-19 pandemic, which resulted in the need for a distribution of vaccines. Some vaccines require storage at ultra-low temperatures (ULT) between -60 °C and -90 °C. Other medical supplies, for example, antibiotics and plasma, require storage temperatures of roughly -20 °C. Therefore, multi-temperature refrigerated containers are typically used to deliver medical supplies globally. Current technologies are characterized by capacity limitations, environmentally damaging refrigerants, inefficiencies and safety concerns. Although low-temperature refrigeration systems still benefit from HFC replacement exceptions, the ongoing phase-down of existing HFC refrigerants requires additional research to identify low Global Warming Potential (GWP) substitutes. This study investigated the use of a reverse Brayton cycle to overcome these issues. The performance of different open air-cycles on the ULT side is computed through a detailed thermodynamic model. Air-cycles have the advantage of being safe and environmentally harmless due to the use of air as a refrigerant. Furthermore, the air-cycle does not need a heat exchanger on the low side, which saves space and eliminates inefficient defrosting cycles. Additionally, the compressor is much smaller compared to compressors used in vapor compression cycles and the cycle architecture is relatively simple, which increases reliability. The proposed system was compared under the same operating conditions to a cascade vapor compression cycle. It was found that the efficiency of the air-cycle is 25% to 41% lower than the cascade vapor compression cycle in the expected operating range. However, the air-cycles have some advantages over the cascade system. The increasing wealth of legislation against HFCs and HFOs has made low or zero GWP refrigerants very attractive. Furthermore, space can be saved due to smaller compressor size and the lack of an evaporator, which can increase the storage volume for transported goods. Lastly, the air-cycles do not have frosting/defrosting losses, which reduces the real performance of the cascade system. Within the air-cycles, both cycle configurations showed very similar performance, which means that the parallel air-cycle configuration is advantageous due to low complexity. Overall, this makes the air-cycle a feasible alternative to more traditional approaches in low-temperature applications and the design requirements must be carefully weighted to choose the ideal system.

1. INTRODUCTION

The COVID-19 pandemic has led globally to a spike in demand for ultra-low temperature (ULT) refrigeration capacity for the long-term storage and transportation of vaccines. According to ASHRAE (2020), temperatures below -50 ℃ for the refrigerated space, can be defined as ultralow-temperature refrigeration. Different solutions were proposed to meet this rise in ULT capacity, ranging from storage with dry ice, to refrigeration systems (Hwang et al., 2022). Refrigeration systems are the only technology that can keep vaccines cold for an extended period or when repeated access to the container is required. With a generator, electricity can be produced, and the vaccines can be transported freely off the grid. A typical two-compartment container refrigeration system, a cascade vapor compression cycle is shown in Figure 1.

In most ULT container applications, a vapor compression cascade system is employed. For instance, Thermo King (2020) developed a refrigerated container which can reach storage temperature of -70 °C. However, the system operates with high GWP HFC’s (R-134a and R32).



(a) (b)

Figure 1: a) Example of a refrigerated container (obtained from: CMA CGM Group), b) Thermodynamic Cascade Cycle, used in most ULT applications.

The ULT refrigeration industry is currently using high GWP refrigerants, since laws such as Regulation (EU) No 517/2014 have excluded ULT applications from the (GWP < 2500) limitation [ARTICLE 11(1), Annex III]. However, it is expected that this will change due to the increased market share of ULT refrigeration and the stricter regulations on HFCs.

An alternative low-GWP option to the cascade system is the air-cycle. An air-cycle is a gaseous cycle which uses air as its working fluid. Air-cycles typically have low thermodynamic performance. However, at large temperature differences, air-cycles can be beneficial over traditional vapor compression cycles. Recently, Refolution and Teledor (2020) designed such a system for a refrigerated container, which operates with an air-cycle and a separate CO_2 booster system for the MT section. These represent the current state of the art and both technologies are investigated.

In this work, we propose to investigate the comparative advantages of different air cycles over conventional VC systems with a particular focus on vaccine storage. Four different air cycles are investigated and compared to a baseline cascade cycle. The performance of the different cycles is compared for varying ambient conditions and advantages and disadvantages of the air-cycle are quantified.

2. SYSTEM DESCRIPTION

2.1 Two-compartment refrigerating container

The container is used to maintain the temperature of vaccines and other medical supplies. The vaccines must be stored between -90 °C and -60 °C (*e.g.*, Pfizer) while other supplies require storing temperatures of -20 °C (*e.g.*, Moderna, plasma, etc.). For this usage, a container with two sections is designed, of which the low temperature (LT) section is kept at -70 °C and the other medium temperature (MT) section at -20 °C. The container will be accessible through one door only so that the MT section can be used as an air lock. This way, when accessing the LT section, the energy loss will be reduced. The container will be used for transportation and stationery storage. It is assumed that a power source with 400 V at 50 Hz is available, commonly available on container ships. Optionally, a generator can be added. In this study, a variety of ambient temperature conditions are modeled. The highest temperature being 50 °C for possible operation in hot climates. Due to global warming, low-GWP refrigerants are the preferred choice in this study.

The low GWP refrigerant group of HFOs such as R-1234yf may lead to byproducts in the atmosphere that concern several scientists (Umwelt Bundesamt, 2021). These refrigerants are increasingly criticized and since their use is controversial, natural refrigerants are seen as advantageous.

2.2 Baseline Cascade System

The cascade system is the state-of-the-art system used in ULT refrigeration and is therefore considered the baseline cycle. Fig. 1 (b) shows a schematic of the cycle. Two refrigeration cycles are coupled with a cascade heat exchanger. Each cycle operates with a different working fluid, which is optimized for its operating range. Mota-Babiloni et. al. (2020) and Bani Issa et al. (2022) describe different configurations and suitable refrigerants of the cascade cycle, where R290 for the high side and R170 for the low side are found to be a climate friendly and efficient option.

The MT evaporator is positioned on the high side cycle. This can be either in series or in parallel to the cascade heat exchanger. If no load is needed at the MT evaporator, the heat exchanger can be bypassed with additional piping.

The cascade cycle as shown in Fig. 1 (b) can be optimized through various different configurations, such as internal heat exchangers, open flash tanks, economizing, etc. Bani Issa et al. (2022) compared the cascade cycle for different configurations and showed that the simple cascade cycle can be improved by 5-25% based on the ambient temperature.

2.3 Air-Cycle

The air-cycle architecture is based on the reverse Brayton cycle. Schematics of the cycle are shown in Fig. 2. Unlike the vapor compression cycle, no phase change occurs in the process. Due to the use of air as the working fluid, the cycle can be operated in an open process in which the cooled air can directly be expanded into the room. This also means that the low side pressure is limited to the atmospheric pressure, hence the high side pressure needs to be optimized for efficiency.

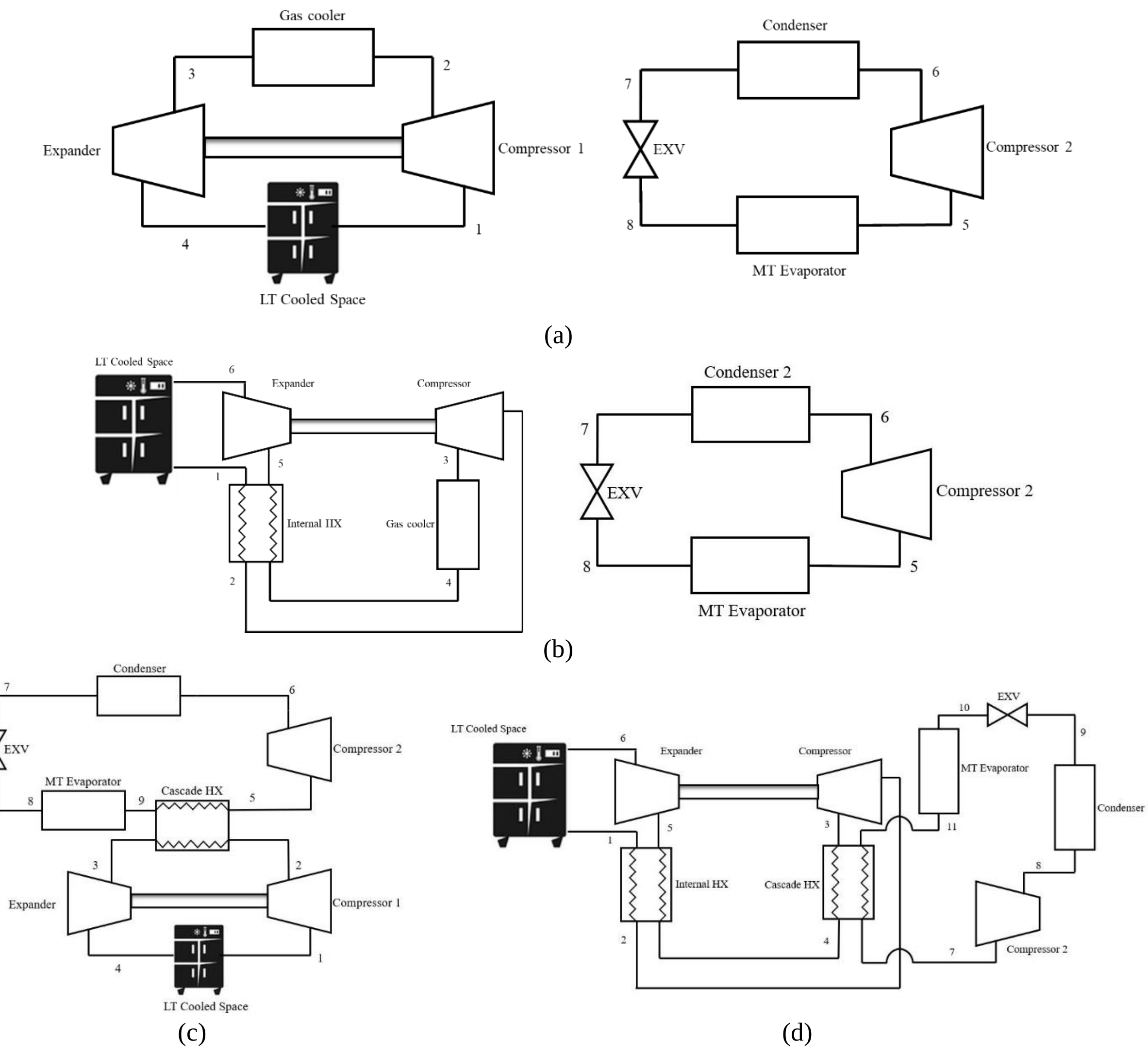


Figure 2: Different thermodynamic cycle configurations investigated in this work, excluding the baseline VC cycle: (a) Parallel Cycle, with air between $T_{ambient}$ - LT and VC to meet MT load, (b) Parallel Cycle, air operating between $T_{ambient}$ – LT with the inclusion of an IHX, and VC to meet MT load, (c) Cascade cycle with air on the LT loop, (d) Cascade Cycle with air on the LT loop and IHX.

Due to the high volumetric airflow, it is beneficial to recover work during the expansion process, which is done with an expander. The pressure difference between high side and low side can be reduced with the use of an internal heat exchanger, the so-called recuperator, as shown in Fig. 2 (b) and (d). With the recuperator, possibly compressor losses can be reduced, and the COP increased.

For the MT section with a room temperature of -20 °C, the temperature difference between ambient and section is relatively low, making the vapor compression cycle superior. Hence, the air-cycle would only be used for the LT section and for the MT section a vapor compression cycle must be installed. For this design, in the MT section a simple 4 component cycle with one stage compression is considered and an air-cycle for the LT section, illustrated in Fig. 2(a). Fig. 2(b) presents the same system as Fig. 2(a) but with the inclusion of an IHX on the air side.

2.4 Cascade Air-Cycle

The cascade air-cycle is similar to the cascade cycle described in Section 2.1. The difference is that on the low side, an air-cycle is employed. The two systems are coupled with a cascade heat exchanger. As opposed to the stand-alone air-cycle, the cascade cycle does not need a separate refrigeration cycle for the MT section. Fig. 2 (c) shows a schematic of the cascade air-cycle and Fig. 2 (d) a schematic of the cascade air cycle with a recuperator on the air side.

2.5 Auto Cascade

An alternative thermodynamic cycle which is a variation of the cascade system is that of the auto cascade. This thermodynamic cycle was not investigated in this work; however, it has seen growing interest for ULT applications (Mota-Babiloni et al. 2020). In the auto cascade cycle, 2 refrigerants with low boiling and high boiling properties are mixed and compressed. In the condenser the refrigerant with the lower condensation temperature, fluid HT in the schematic, condensates while the other refrigerant remains in a superheated state. In the following phase separator, the refrigerants are separated, and the liquid phase HT refrigerant is expanded. In a heat exchanger, the evaporative condenser, the gaseous refrigerant, fluid LT, is condensed with the now expanded and cold HT refrigerant. With further expansion, the LT refrigerant can now achieve ultra-low temperatures.

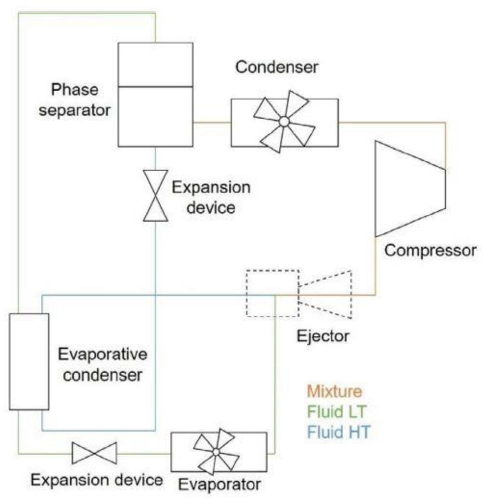


Figure 3: Auto-cascade cycle with or without an ejector, adapted from Mota-Babiloni et al. (2020).

The pressure difference between high side and low side can be reduced with an ejector as shown by Mota-Babiloni et al. (2020). In the studies performed by Liu and Yu (2018) and Liu et al. (2018), possible configuration and cycle improvements with different ways of making use of the ejector are presented. However, the researched auto-cascade systems so far only consider a single evaporator usage. The vaccine container in this study operates in two temperatures, and therefore either a novel auto-cascade system needs to be designed or an additional cycle for the MT section needs to be installed. This system can be investigated as part of future work on two-compartment systems.

3. THERMODYNAMIC MODELING

A steady state thermodynamic model is developed to compare the investigated cycle architectures. The systems are modeled with the program Engineering Equation Solver (Klein, 1992), which has its own library of thermodynamic properties. In all models, assumptions are made with the aim of a fair comparison between the different cycles. For the compressors, constant isentropic efficiencies were assumed, based on the compressor pressure ratio. The air to refrigerant heat exchangers were modeled with a constant pinch temperature of 10 K. The cascade heat exchangers and internal heat exchangers were modelled with the effectiveness-NTU method. In all models, pressure drops were neglected. Assumptions for all cycles are listed in Table 1.

The COP of all systems is calculated with the total cooling capacity of both refrigerated sections and the total power consumption or production of all components. For the non-air systems, isenthalpic expansion with no work recovery is assumed.

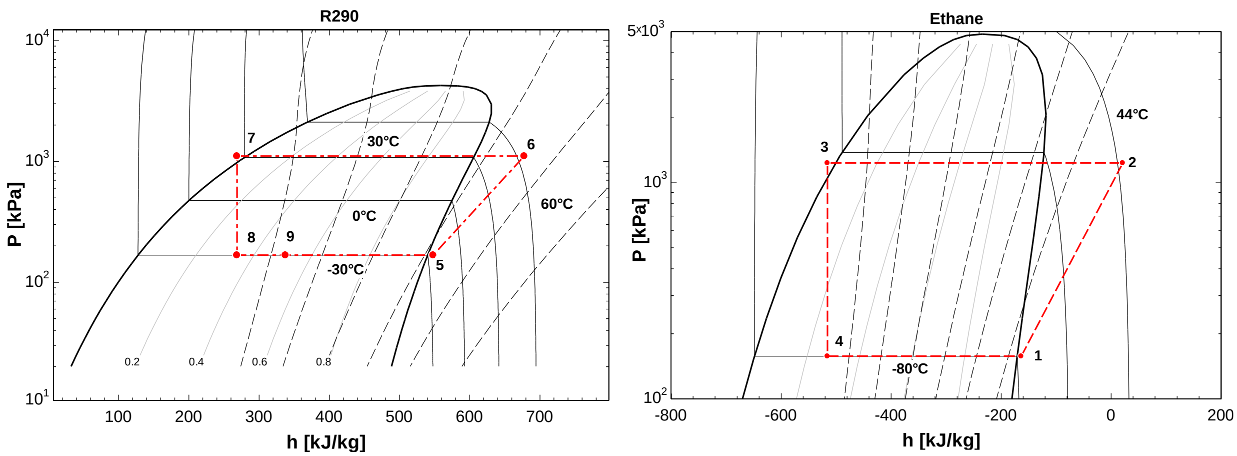
$$COP = \frac{\dot{Q}_{MT} + \dot{Q}_{LT}}{\sum_i \dot{W}_{comp,i} - \eta_{mech} * \dot{W}_{turb}} \tag{1}$$

Table 1: System Modeling Parameters

Parameter	Location	Value
Heat exchanger effectiveness	Cascade heat exchanger	0.8
Heat exchanger effectiveness	Recuperator	0.92
Temperature Pinch	Refrigerant to air heat exchangers	10 K
Compressor isentropic efficiency	Air-Cycles	0.84
Compressor isentropic efficiency	R290 and R170 Compressors	0.7
Mechanical losses	Between turbine and compressor	0.99
Turbine efficiency	Air-Cycle	0.89
Pressure drop	All Systems	Neglected
Superheat	MT and LT evaporator, Cascade HX (high side)	5 K
Subcooling	Condenser, Cascade HX (Low side)	5 K
	Boundary Conditions	
Ambient temperature (HT)		-10 to 50 ℃
Average ambient temperature		20 ℃
Medium Temperature (MT)		-20 ℃
Low Temperature (LT)		-70 ℃
Cooling capacity MT		2/3 RT or 2.34 kW
Cooling capacity LT		4/3 RT or 4.64 kW
Total container capacity		2 RT or 7.03 kW
Pressure LT Section		101.325 kPa
	Refrigerants	
Parallel Air Cycle	MT	R290
	LT	Air
Cascade Air Cycle	MT	R290
	LT	Air
Baseline Cascade Cycle	MT	R290
	LT	R170

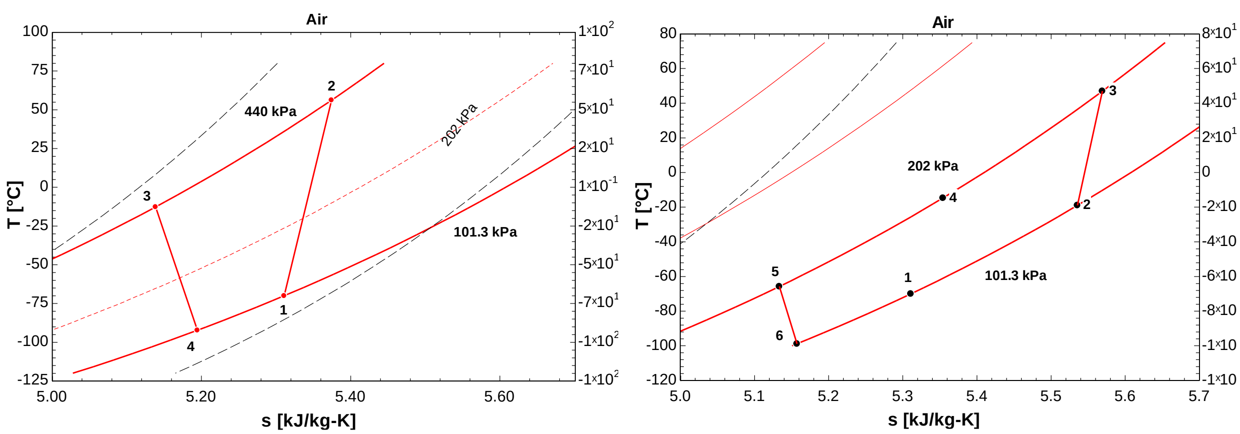
4. RESULTS

Using the discussed methods, five different cycles were modeled, the cascade baseline, parallel with and without recuperator and cascade air with and without recuperator. Fig 4 shows the P-h plot of the baseline VC cascade system at an outdoor temperature of 20 °C. It can be seen why the cascade configuration is needed for the ultra-low temperature section. The refrigerant R290 is not suitable for an evaporating temperature of -80 °C because the pressure is below atmospheric.
Furthermore, on the low side, the ethane (R170) discharge temperature increases drastically with a higher cascade temperature. In the operating condition, a very large pressure ratio of 7.9 exists. Hence, the intermediate cascade temperature should not increase much more, to avoid inefficiencies.
Fig. 5 shows the T-s plots for the two configurations of the cascade air-cycle at a temperature 20 °C with or without recuperator. The state points are indicated in Fig. 2. The baseline cycle overcomes a very large temperature, to reject its heat. In comparison, the air-cycle with recuperator has a significantly lower pressure ratio of 2, compared to a pressure ratio of 4.4 for the cycle without recuperator. This speaks for much-reduced entropy losses and shows that the recuperator implementation is a necessity from an efficiency standpoint.



(a) (b)

Figure 4: P-h plot of the Baseline Cascade (VC) at 20 °C outdoor temperature, (a) MT system, (b) LT system.



(a) (b)

Figure 5: T-s plot of the air-cycle at the LT side, (a) without a recuperator, (b) with a recuperator, at 20 °C outdoor temperature.

For all investigated cycles, the COP was evaluated at different outdoor temperatures. A summary of these results is shown in Fig. 6. For the air-cycles, the high side operating pressure was optimized at each temperature for COP with the in EES implemented Min/Max function. The results show that the baseline cascade cycle has a higher COP than the cycle configurations operating with an air-cycle. It can be distinguished between air-cycles with and without

recuperator, where the systems without recuperator show a very low efficiency. The parallel air-cycle and the cascade air-cycle have very similar COP at all operating temperatures. This contradicts the findings by Gianetti et al. (2017) who predicted higher efficiency for the cascade air-cycle. The deviation can be the result of different assumptions for the model. Overall, the increased complexity of the cascade air-cycle over the parallel air-cycle configuration does not seem justified since the performance characteristics of the two systems are nearly identical. At very high outdoor temperatures, the COP of the air-cycles with recuperator comes close to the COP of the baseline cascade system, with a difference in COP of 12%. For lower operating temperatures, such as an outdoor temperature of -10 °C, the air-cycle gains less COP, compared to the cascade systems. This shows that air-cycles are favorable at very large temperature differences, whereas conventional vapor compression cycles are more favorable for lower temperature differences.
It is expected that at very large temperature differences the air-cycle with recuperator has an efficiency advantage over the cascade system. This could be the case for coolers operating below -100 °C at high outdoor temperatures.
However, the boundary condition of 50 °C is an extreme case, and in the expected normal operating temperature range between 5 °C to 35 °C, the baseline cascade cycle is 25% to 41% more efficient under the given assumptions.

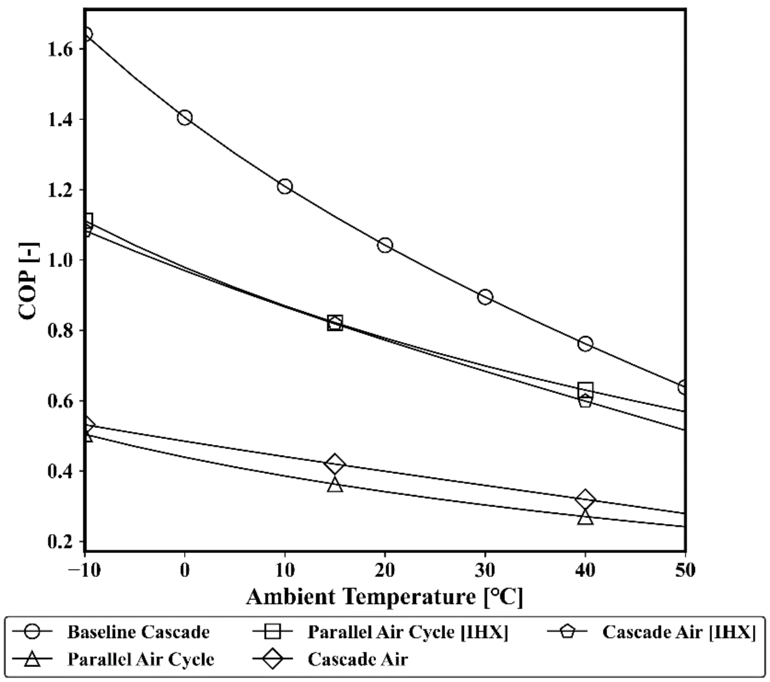


Figure 6: COP of different system architectures in dependence of outdoor temperature

5. DISCUSSION

In this study for an ultra-low temperature refrigerated container the cascade system and different air-cycles were investigated. The auto-cascade is mentioned as a potential 3rd option to these systems and has promising efficiencies, however the complex system architecture, especially for multi evaporative cooling, has its disadvantages. Hence, this cycle was not investigated with a detailed model, even though it could show potentially higher efficiency compared to the cascade system.
The two different configurations of the air-cycle, the stand-alone (parallel) air-cycle and the cascade air-cycle showed very similar efficiencies throughout the operating temperature range. This can change based on the accuracy of the assumptions made in this analysis, however, the increased complexity of the cascade air system does not justify the configuration as a cascade. The cost of a cascade air-cycle is also expected to be increased, due to the larger compressor required on the high side and the cascade heat exchanger. Therefore, the results show that the stand-alone air-cycle with a separate refrigeration system for the MT section is preferable.
In comparison to the baseline cascade system, the thermodynamic analysis showed lower efficiency of the air-cycle compared to the state-of-the-art baseline cascade cycle. With cycle modifications, the baseline cascade system can be further optimized, as investigated by Bani Issa et al. (2022), making the cascade cycle even more advantageous in terms of energy efficiency.

Nevertheless, the air-cycles have some other advantages over the cascade cycle. The cascade system has a limited choice of available refrigerants, that are suitable for the ULT container application. Refrigerants widely used today in this application are climate damaging due to a high global warming potential. Forthcoming regulations prohibit the use of these high GWP refrigerants and alternatives must be chosen. The proposed new low GWP refrigerant class of HFO refrigerants, are increasingly criticized for environmental damaging impacts and are therefore, not seen as a valid future proof alternative (Yishuang Duan, 2020). So far, there has not been a refrigerant that is climate friendly, non-toxic and non-flammable and such refrigerant is not expected to be discovered. Bani Issa et. al. (2022) finds the natural refrigerant combination of R290 and R170, as modeled in this paper, the best choice under these conditions. However, the high flammability of these refrigerants posseses a risk and requieres additional safety considerations and additional training for operating the container. This can increase the likelihood of failures especially during transportation and increase overall costs.

The air-cycle can avoid this, as this cycle can be designed completely safe and environmentally friendly with natural refrigerants for the ULT container. The ULT section operates with air as its working fluid, which does not require any safety features. The -20 °C MT section could be operated with a separate CO_2 system, which is efficient, climate friendly and safe. In the transportation sector this is a large advantage over the cascade system, operating with either climate damaging or flammable refrigerants. Another advantage of the air-cycle is the absence of an evaporator. The cold air is directly expanded into the cold room. This has multiple advantages over cycles with an evaporator. Without the evaporator, space within the room can be saved. In transportation, especially vaccine transportation, space is of high importance. More vaccines can be transported which could justify potentially increased power consumption. Furthermore, evaporators require defrosting. The efficiency degradation of defrost cycles has not been considered in this thermodynamic analysis. This would further decrease the efficiency of the cascade cycle. Defrost cycles can also induce temperature fluctuations within the container. Such temperature fluctuations must be kept at a minimum for vaccines, to avoid spoilage of the vaccines. If the cascade cycle is not designed well, the temperature fluctuations during defrosting could lead to temperatures out of the tolerated range for the transported vaccine. On the contrary, the air-cycle will also collect frost. However, this frost can be collected with a filter and easily transported outside, while still maintaining operation.

The air-cycle also uses less space for the compressor. Air-cycles can use a combined turbo compressor and turbo expander, which are much more compact than conventional compressors at the same cooling capacity. This further increases the available space for transport goods.

The air-cycle setup also has reduced complexity due to the two separate refrigeration system setup. The ULT and MT systems can operate individually, which is advantageous in case of a failure. Additionally, both systems are fairly simple with one stage compression, which increases robustness.

The cascade system, due to its design, requires more advanced controlling and the whole system will fail in case of an error.

6. CONCLUSION

Overall, the baseline cascade system showed higher efficiency over the air-cycle for the ULT application. However, for the specific application of ULT vaccine storage containers, the air-cycle has certain advantages over the cascade system. Both cycle architecture are valid options for the ULT transport container, and the design requirements have to be carefully evaluated and weighted, to choose the best system. Following is a summary of the results:

- The baseline cascade system is 25% to 41% more efficient than the air-cycle in the expected operating range.
- The COP of the air-cycle without recuperator is not sufficient and a recuperator must be used.
- The COP of the air-cycle with recuperator in a parallel configuration is very similar to the COP of the air-cycle with recuperator in the cascade configuration, but it has lower system complexity and is therefore to be preferred for most practical applications.
- In terms of refrigerant selection, the air-cycle is the only system which can operate environmentally friendly and safe. The cascade cycle is dependent on either high-GWP or flammable refrigerants.
- The air-cycle uses less space, due to the lack of an evaporator and more compact compressor, increasing space for transportation goods.
- The air-cycle does not require defrosting, which reduces the gap in efficiency to the baseline cascade system.
- Defrosting cycles of the cascade system potentially spoils vaccines due to temperature fluctuations. The air-cycle can keep its temperature constant better due to the lack of evaporator.

- The auto-cascade system could be an efficient alternative to the cascade system; however, it needs more investigation. Research is limited, especially for a multi evaporator setup.

NOMENCLATURE

$\dot{m}_{flow}$	Mass flow (kg/s)
T	Temperature (°C)
h	Enthalpy
s	Entropy (kW/kg-K)
p	Pressure (kPa)
$\dot{W}$	Work (kW)

Subscripts

$cond$	Condenser
$comp$	Compressor
$turb$	Turbine (Expander)
HS	High Side
HT	High Temperature (Ambient)
LS	Low Side
LT	Low Temperature (-70 °C)
MT	Medium Temperature (-20 °C)

Acronyms

COP	Coefficient of Performance
GWP	Global Warming Potential
HC	Hydrocarbon
HFO	Hydrofluoro-olefin
HFC	Hydrofluoro-carbon
HX	Heat exchanger
IHX	Internal Heat Exchanger
R290	Propane
R170	Ethane

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